Fisheries Research Vessel Hull and Propeller Design To Maximize Hydroacoustic Survey Efficiency

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Abstract - **The authors review the need for a quiet fisheries research ship to protect and maintain fish stocks and marine mammals. The ship design, construction, and acquisition processes are presented in overview. The main mission of the Fisheries Research Vessel (FRV) depends greatly on acoustic sensor performance. A major concern in achieving maximum efficiency from modern acoustic sounders is the reduction of bubbles and the control of bubble sweepdown patterns that flow over the acoustic sensors. The authors describe how the design of NOAA's Fisheries Research Vessel, FRV 40 takes advantage of many previous hydrodynamic and ship design developments. A discussion of subsequent model tests to verify the design is included**

I. INTRODUCTION

    Critical to the development and management of a sustainable fishery is the ability of scientists to evaluate and predict fisheries stocks. For nearly 120 years, the National Marine Fisheries Service (NMFS) and its predecessor organizations have used research vessels to acquire both fishery stock assessment data and oceanographic data to aid in fishery management. The aging of the present fleet, most of which was built in the 1960's, together with advancements in fisheries research technologies prompted NMFS to investigate new developments in modern Fishery Research Vessel (FRV) designs.

     Beginning in 1993, NMFS, a line organization of the National Oceanic and Atmospheric Administration (NOAA), conducted a thorough examination of recently developed fisheries research vessels in other countries [1]. The uniqueness of scientific research for fisheries demands that FRVs support the mission of collecting both stock assessment data and environmental data simultaneously. Functional requirements identified by NMFS for a modern fisheries research vessel are acoustic quietness to reduce fish avoidance, new hydroacoustic surveying technology, trawling capabilities, over-the-side sampling and state of the art computer systems. Fisheries research vessels must have the ability to stay on station for long periods of time through the use of dynamic thrusters and provide stability for sensitive instrumentation in various sea states. In addition, modern FRVs must be built to accommodate future advancements in stock assessment techniques, such as 360º sonar. Recent technological design advancements in ocean going research ships greatly enhance the quality of scientific data needed to support management decisions.

    The worldwide interest in fisheries research has increased dramatically in the last 10 years. The UK, Norway, Iceland, Ireland and others have constructed or are building new FRVs with low underwater radiated noise signatures. NMFS is in the process of constructing the first of a new class of acoustically quiet FRVs for the US. Hydroacoustic surveys are predicted to play a major role in stock assessment in the new millennium. The International Council for the Exploration of the Sea (ICES) has developed an underwater radiated noise standard for all vessels used for fisheries research [2]. The noise standard was developed based on a review of over 75 references relating to the reaction of fish to noise and more than 260 additional references, all in the scientific literature. If vessel quieting is ignored, both scientific and survey results will be suspect. The primary emphasis on vessel quieting is associated with impacts on fish behavior rather than on aspects related to the operation of quantitative echosounders. The

primary portion of the vessel quieting requirement is in the 10 to 1000 Hz range. In this frequency range, there is no impact on the operation of the acoustic systems of the vessel, but the effect of ship noise on fish behavior can be very significant. This low frequency quieting of the research vessel is aimed at improving surveys of fish populations using any survey technique.

A major concern in achieving the maximum efficiency from modern acoustic sounders is the reduction of bubbles across transducer faces, the control of bubble sweepdown patterns, and the reduction of cavitation bubbles. The FRV 40 design takes advantage of many previous hydrodynamic and ship design developments. A centerboard is used to deeply immerse many of the sensors below the bubble path. Navy experience was used to develop a new hull form to minimize bubble sweepdown and improve the performance of the remaining hull mounted sensors. Other hydrodynamic efforts, such as improving the inflow to the propeller, improving the flow over the centerboard, and minimizing propeller cavitation were also undertaken. A series of model tests were performed to verify the calculated performance of the design.

II. NOAA FRV PROGRAM OVERVIEW

The FRV replacement program team conducted a thorough analysis of the current and future data acquisition needs and developed a set of overall ship operational and scientific requirements [3]. A wide range of both operational and scientific needs was distilled into an achievable set of requirements for a common platform that could satisfy most of the needs of all six major eco-system regions managed by NMFS under its legislative mandates. Difficulty in developing a quiet hull form provided a great incentive to utilize this common platform to amortize the high cost of meeting the stringent radiated noise criteria of ICES. Both the requirements definition and concept design efforts were aided significantly by a thorough mission analysis that provided design driver boundaries and operational capacities for both engineers and scientists to use. While the requirements were being validated, NOAA conducted a concurrent engineering effort to assure feasibility of the proposed ship solutions with multiple iterations of layouts and potential arrangements to assure operational requirements would fit and be complementary to the hull form and propeller development described below.

This work resulted in a solicitation and contract award for the lead ship of the FRV 40 Class with options for up to three additional ships. The US Congress has appropriated funds for the first ship and is considering NOAA budget requests for the additional ships. Halter Marine, Inc. has begun the detailed production engineering with the expectation of laying a keel in April 2002 and subsequent delivery in January 2004.

III. HYDRODYNAMIC DESIGN CONSIDERATIONS

A. *Bubble Sweepdown*

The term "bubble sweepdown" refers to the tendency of nearly neutrally buoyant bubbles that are in the path of a ship to be swept under the ship's hull by the flow field surrounding a moving ship. This tendency occurs on all ships. For ordinary merchant ships it is of no consequence. However, on ships that are outfitted with underwater acoustic transducers the

bubbles can significantly degrade the effectiveness of transducer performance. On many specialized vessels, such as oceanographic survey and research vessels, warships and fisheries survey and research vessels, bubble sweepdown is an important consideration for both the placement of sensors and the design of the hull form. The design of the NOAA Fisheries Research Vessel, FRV 40, took advantage of past experience and modern numerical computational methods to develop a hull form to minimize the impact of bubble sweepdown.

B.   Bubble Origin and Bubble Path
        In order to understand the analysis and evaluation of bubble sweepdown problems it is helpful to understand the origin and nature of air bubbles in water. Bubble generation has been attributed to the following sources:

- The action of naturally occurring surface wind and waves results in a layer of water near the surface that has air bubbles.
- The bow wave motion from ships captures air from the surface and mixes it with the water to form bubbles.
- Ventilation or cavitation from the free surface, such as from an improperly designed stem, results in bubble formation.
- Cavitation or flow disturbance from an underwater appendage, such as a bow thruster opening.

    Ship motions, especially pitching, can aggravate and add to the above listed mechanisms. In addition, the upward pitching motion has been observed to cause the formation of an underwater vortex near the bottom of the bow, with the vortex subsequently breaking up into bubble clouds.

    Efforts directed toward minimizing bubble sweepdown through hull design have mostly concentrated on minimizing the effects of air bubbles that originate near the bow and close to the water surface. These efforts require determination of the streamlines that will carry the bubbles downstream. The objective is to design a hull shape that directs these streamlines as far away from acoustic sensors as possible.

    Bubbles have buoyancy and an associated rise rate. Therefore, they will have a tendency to follow a path that is slightly above the streamline. The terminal velocity of air bubbles rising in a calm unbounded environment varies with bubble size [4]. The terminal velocities range from 1.5 cm/sec for 0.01 cm equivalent radius bubbles to 55 cm/sec for 3 cm equivalent radius bubbles. For very small radii and velocities that correspond to a Reynolds number less than 70, the bubbles have a drag coefficient the same as that of a solid sphere. At higher Reynolds numbers the bubbles flatten out into mushroom shape and their drag differs from that of a solid sphere.

IV. THE NOAA FRV 40 DESIGN

    The NOAA FRV 40 design has the following nominal dimensions: 63.4 m (208 ft.) length, 5.4 m (17.7 ft.) draft midships, and 2520 mt (2380 LT) displacement. The propeller diameter is 4.3 m (14.1 ft.) and the block coefficient is 0.478. This design includes keel drag of 2.69 cm per 100

cm. The Naval Surface Warfare Center (NSWC) was contracted by NOAA to assist with hydrodynamic model testing and design aspects of the FRV 40 hull to utilize the results of previous work. Using a 1/13 scale, a 15 ft hydrodynamic model was constructed. This model was one of the first to be inspected by a three-dimensional laser scanning process. The hull surface of the model was verified to be within 0.02 inch of the desired surface, with a maximum deviation of 0.04 inch, which is well within the acceptable accuracy of such a model. Highlights of the design and testing efforts are summarized herein.

A. Bow Shape To Minimize Bubble Sweepdown

NSWC designers used their past bubble sweepdown experience to design an alternative bow shape to minimize bubble sweepdown effects on the hull mounted acoustic sensors. The initial forebody and the bulbous forebody shape shown in Fig. 1a were developed. A free surface potential flow code program was used to analyze the streamlines on both bow shapes. This program accounts for the bow wave and provides a good prediction of streamlines in the bow region. Fig. 1b shows a comparison of a streamline on the two bow designs. In each case the streamline originates 0.5 m below the 5.9 m design water line. On the original hull the streamline almost crosses the bilge radius by station 6. With the bulbous forebody the same bow streamline is approximately 1 meter further away laterally from the transducer location at station 6. Prediction of the ship resistance at the 11-knot survey speed showed that the bulbous forebody bow increased the total ship resistance by approximately 1 percent. The increase is equally due to an increase in wave resistance and an increase in frictional resistance resulting from more wetted surface. The 1 meter improvement in streamline location was judged to be far more significant than the small additional resistance, and, therefore, the bulbous forebody bow design was selected.
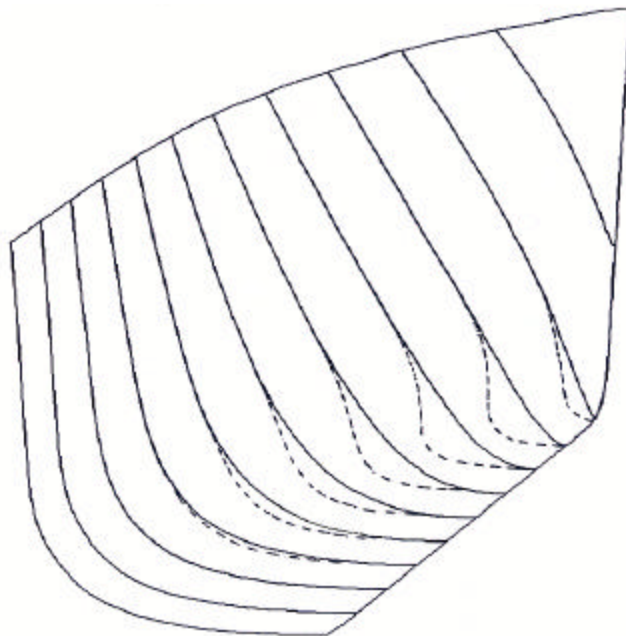

Fig. 1a. FRV 40 forebody with conventional V-shaped bow sections and with U-shaped sections for minimum bubble sweepdown
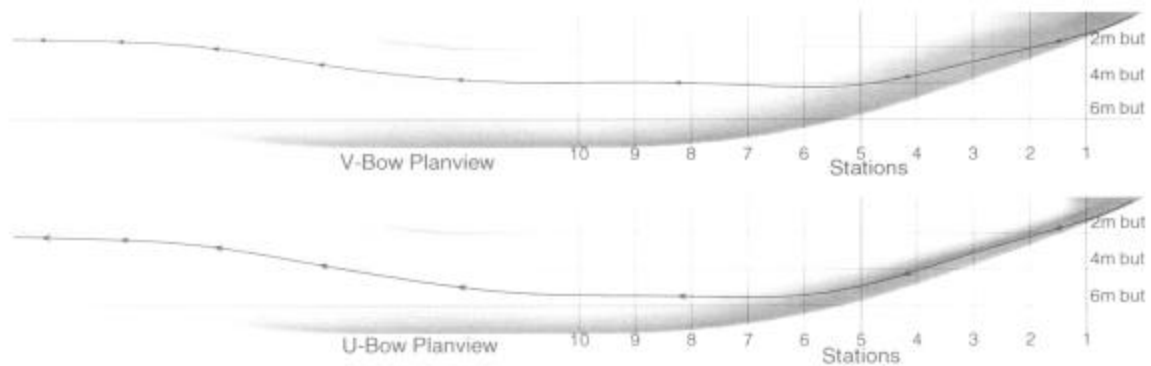
Fig. 1b. Comparison of potential flow streamline on the two forebody shapes of the NOAA FRV 40 (11 knot ship speed)

Model bare hull resistance experiments were undertaken. For the FRV 40, the bare hull includes the skeg that houses the propeller shaft. The resistance results were compared to the NSWC computerized database of hull forms. The comparison was made relative to 319 hull forms in comparable categories, including escorts, trawlers, minesweepers and oceanographic ships. The comparison is based on the coefficient Cpe, which is the ratio of resistance of the subject ship to that of an equivalent Taylor Standard Series Ship [5]. In this way, all the hull forms are compared to a common standard, the Taylor Series hulls, and the Cpe coefficient provides a measure of form influence rather than the influence of a geometric characteristic such as length, beam, or draft. At the 0.78 speed-length ratio corresponding to the 11 knot quiet operating speed, the FRV 40 had the fourth lowest value of Cpe of the 319 hull forms. However, the other three lower resistance hull forms appear to be unrealistic for FRV purposes because they have no transoms. In addition, the three other hull forms have no skeg with its integral propeller support. The addition of shafts and struts or an integral skeg would probably raise their Cpe comparison value to a value greater than the FRV 40. Therefore, the authors conclude that the FRV 40 hull form is truly the best hull form to satisfy the mission requirements.

Fig. 2 is a photograph of the model bow taken during stock propeller model tests. The bow wave associated with this initial configuration shows an unusually large blunt wave form with a turbulent character. The bow was subsequently made finer, principally forward of station 3, by increasing the steepness of the stem angle and lengthening the lower waterlines. The bulbous forebody character of the lines was retained, see Fig. 3. With the new bulbous forebody shape the blunt wave form and turbulent nature of the bow wave were reduced. The peak wave height along the hull decreased by 7 percent. Based on the flow observations, it is assumed that this elongation of the bow reduced resistance.
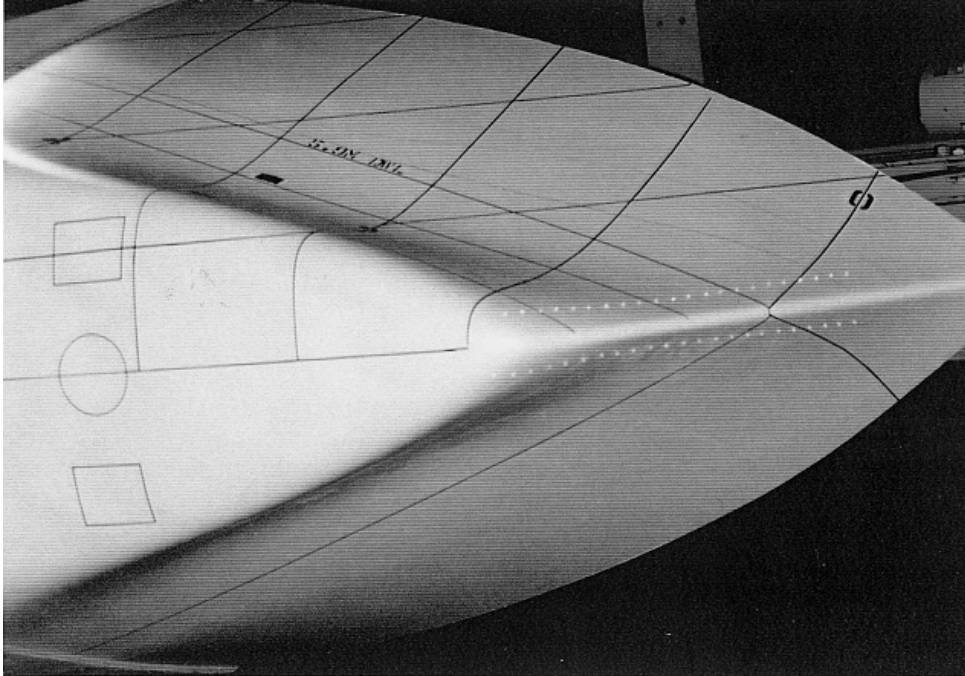
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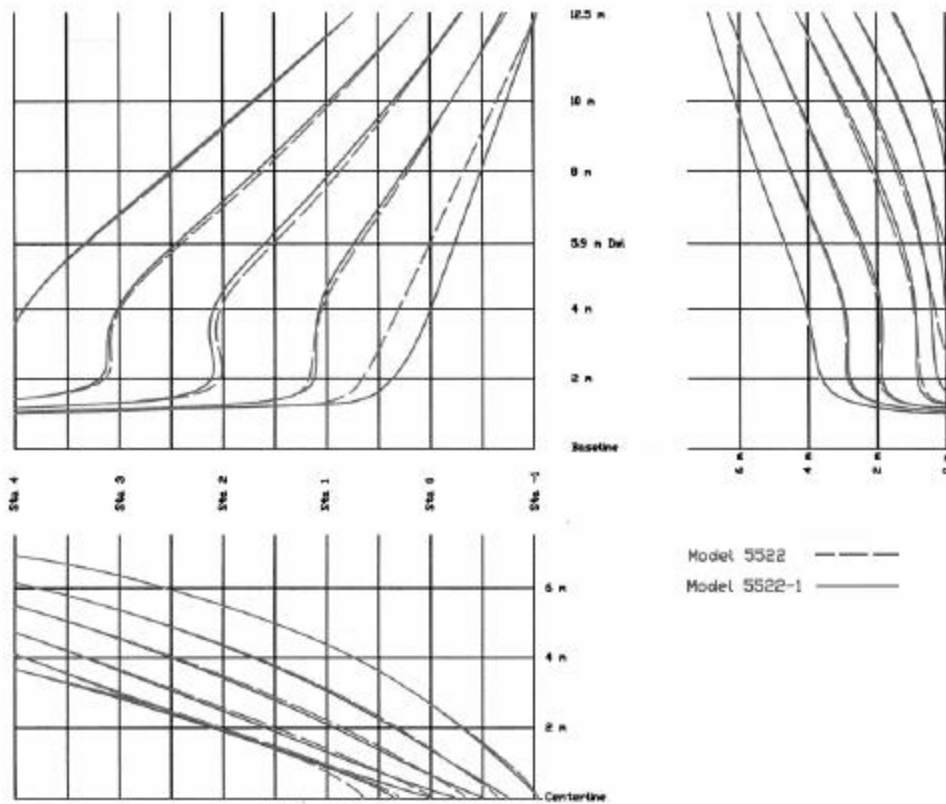Fig. 2. FRV 40 model showing bulbous forebody (model 5522)

Fig. 3. Partial lines drawing showing NOAA FRV 40 bow modification

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B. Skeg Design

NSWC was also asked to evaluate the detail design of the skeg in order to minimize flow disturbance to the propeller. A propeller cavitation inception speed occurring above the speed at which the vessel conducts fish population sampling using acoustic sensors is critical to the mission success of the vessel. Two skeg designs were proposed. The first, shown in Fig. 4, is the baseline skeg based on experience gained from the US Navy Sealift Technology Development program. This skeg features a large bulbous underwater form with parallel sides and mostly single curvature surfaces. There is a very fine web connecting the bulbous skeg and the hull.

The second skeg design, labeled DTMB4, Fig. 5, was the fourth iterative design variation on the baseline skeg using the ISFLOW viscous flow code program. The ISFLOW program and the model test results showed only small differences in the wake of the two skegs. Both were very good designs. The axial wake deficit of skegs is very small, and is more typical of good wakes from shaft and strut appendages than from a skeg appendage. The baseline skeg was selected because wake near the propeller tip radius, shown in Fig. 6, is just slightly better, and the baseline skeg is easier to build due to its single curvature surfaces
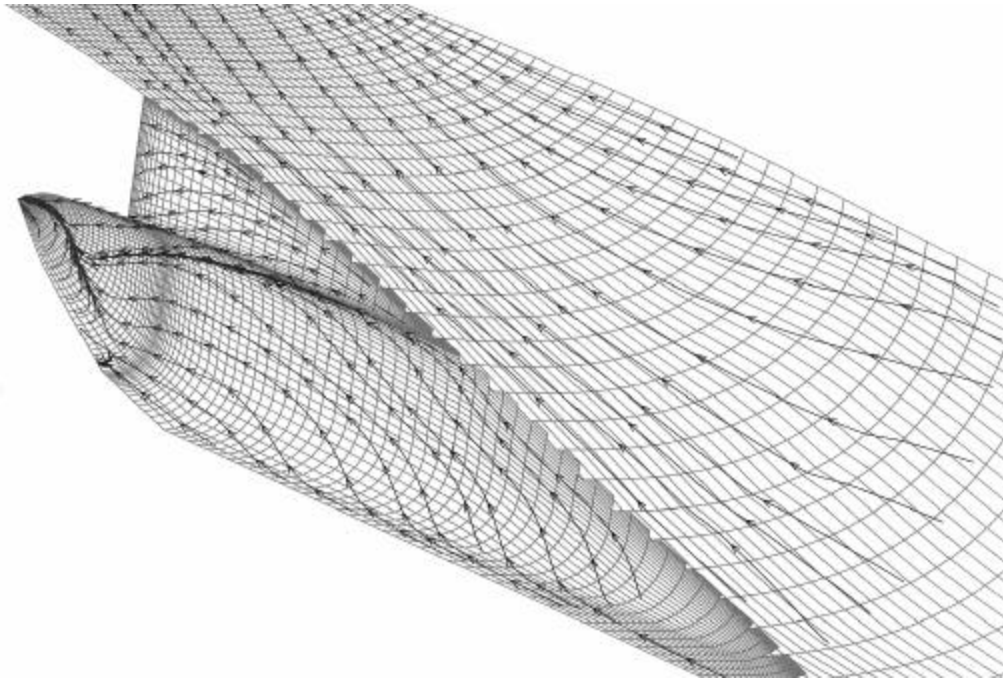

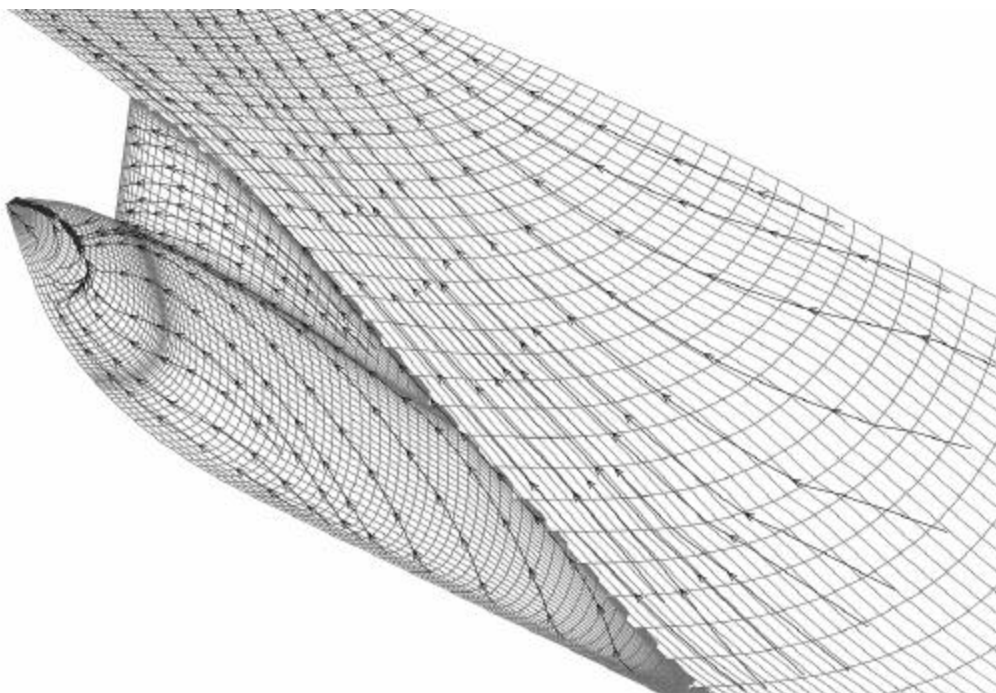Fig. 4. Streamlines on the baseline FRV 40 skeg
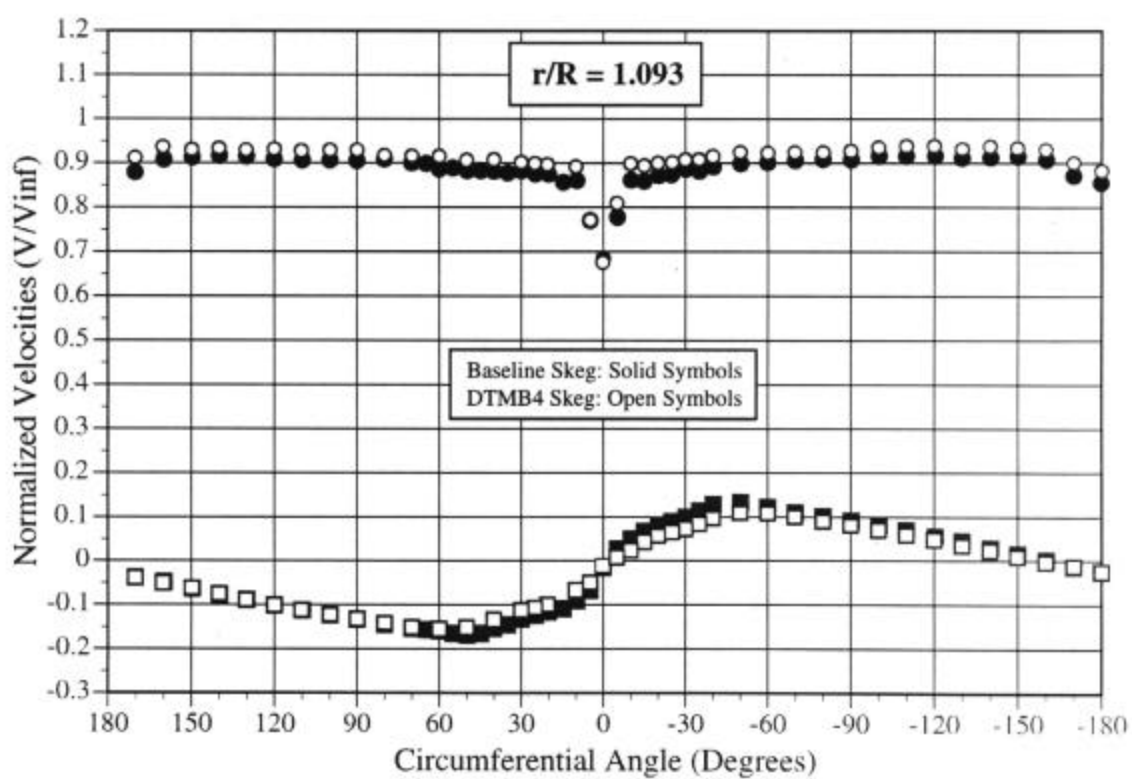
Fig. 5. Streamlining on DTMB4 FRV 40 skeg

Fig. 6. NOAA FRV 40, comparison of axial and tangential velocity component ratios. DTMB4 skeg versus baseline skeg

C. Bilge Keels

The bilge keels were aligned during the model test phase using traditional oil dot streamline traces.   In order to reduce drag, the bilge keels were subsequently reduced to approximately 50 percent of their original length. A roll damping analysis that took into account the damping effect of the centerboard indicated that the shorter bilge keel would be adequate.

D. Centerboard

The centerboard is a retractable foil approximately 3.2 m long and extending 3.75 m below the vessel. It houses a variety of acoustic sensors mounted on its bottom. The deep sensor location away from the hull minimizes any bubble sweepdown problem and distances the sensors from radiated noise sources. The initial design evaluated during model tests had a National Advisory Committee for Aeronautics (NACA) 66 form and thickness ratio of 27.4 percent. Underwater flow visualization model tests using tufts revealed a flow separation problem on this design. The centerboard and the associated sensor arrangement were redesigned to a 22 percent thickness ratio section, reducing centerboard drag by 36 percent. At 11 knots the thinner centerboard accounted for only a 5.8 percent increase in drag over the bare hull resistance.

E. Rudder

For physical fish sampling and identification of specific species, the FRV 40 has a requirement to tow a net and catch fish at 4 and 5 knot speeds. A tow load of 160 kN (39,900 lb) was specified. In order to have as much maneuvering control as possible under these conditions a high lift rudder with a fixed split trailing edge flap and end plates was designed. This initial design had flow separation at the trailing edge, as shown by tufts in underwater flow visualization model tests. At 11 knots ship speed, the drag of this rudder represented an 11 percent increase over the bare hull drag. To reduce this drag, a new actuated flap rudder model was tested. The new design contributed only 6 percent resistance over the bare hull, and was adopted to capitalize on the long term fuel efficiency benefit.

F. Stock Propeller Powering and Wake Survey

These model experiments were undertaken to aid the propeller design by defining the inflow to the propeller and defining the required propeller thrust. In addition, these experiments provide an initial estimate of speed and power. A trial speed of 14 knots was predicted with the stock propeller at 2242 kW delivered power in the 2520 mt displacement condition.

The nominal wake data for the baseline skeg is shown in Fig. 7 [6]. The wake data for the outer radii are most critical. This hull and skeg combination has very good wake characteristics normally found only with a strut propeller support. The relatively large wake deficit in the 180 degree position is partially due to the preliminary centerboard design, subsequently shown to have flow separation. However, the 180 degree position was not the controlling position for the propeller design.
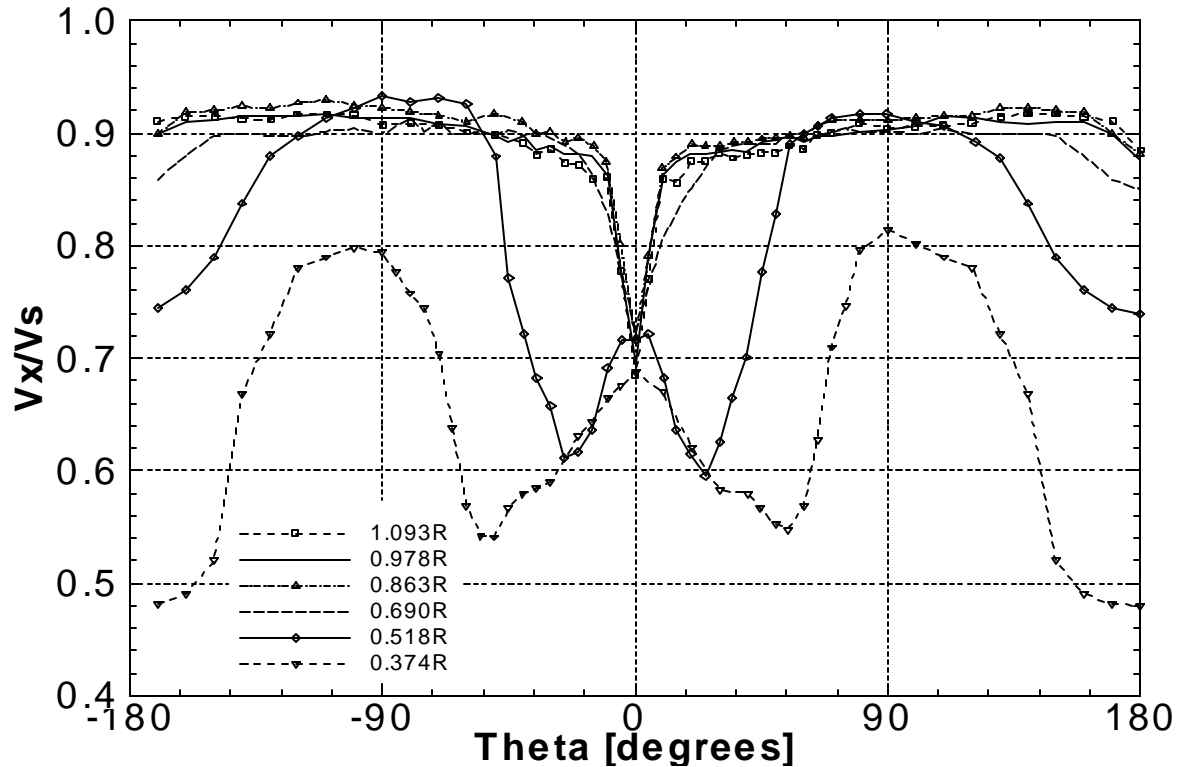
Fig. 7. FRV 40 wake data, 0 degree position at the top of the propeller disk

G. Propeller Design

   Overall performance requirements for the propeller included being cavitation free at 11 knots and maximum efficiency for both free running and trawling. The propeller cavitation at all other operating points was also to be minimized to assure fish behavior modification could be minimized during sampling. Required shaft thrust obtained from the stock propeller powering tests is given below.

Ship Speed	Shaft Thrust
11 knots	26,500 lb.
13.45 knots (85 % power)	46,400 lb.
14 knots (full power)	52,500 lb
4 knot towing	40,800 lb.

   Preliminary efforts quantified a trade-off between various propeller characteristics such as diameter, RPM, blade number and blade area. The most critical design criterion was the 11 knot ship survey speed with an efficient propeller and with no propeller cavitation. Design features incorporated in order to achieve these goals include an unloaded propeller tip, the largest possible propeller diameter, RPM as low as possible, long chord lengths, and a tip bulb. Initial calculations indicated that 7 blades were preferable from a tip vortex cavitation point of view. However, 5 blades were also acceptable and chosen by NOAA as more conventional and preferable for manufacturing.

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Because of the 4 and 5 knot trawling requirements in addition to the 11 knot survey speed there was an initial perception that a controllable pitch propeller would be needed. Several open water propeller performance characteristic curves were calculated for a range of pitch angles. Adjusting the pitch at the tow condition did not provide any benefit. For the free route (no tow) 14 knot maximum speed condition, a 4 percent improvement in propeller efficiency was achievable for the controllable pitch propeller. This powering improvement, however, would be somewhat reduced by the effect of the larger hub and extra weight of the controllable pitch propeller. The powering benefits were insufficient to justify the added complexity and cost of the controllable pitch propeller. Scientifically, a consistent and repeatable noise signature from a fixed pitch propeller adds an additional benefit and eliminates a variable.

The propeller was designed using current lifting line and lifting surface propeller design programs. The geometry of details such as fillets, tip bulb and anti-singing trailing edge were carefully defined. The structural requirements were determined by ABS rules for vessels under 90 meters, and blade stress calculations were performed using beam theory. ABS rules for Ice Class C0 have been applied.

A computer rendering of the final propeller design is shown in Figs. 8a and 8b and the geometric characteristics are shown in Fig. 9. The cavitation performance of this propeller is predicted to have a leading edge cavitation inception speed over 14 knots, a tip vortex cavitation speed of 13.9 knots with little hub vortex cavitation. At the 4 knot towing there will be minimal leading edge cavitation. In addition, the propeller will have low unsteady blade rate forces as given below:

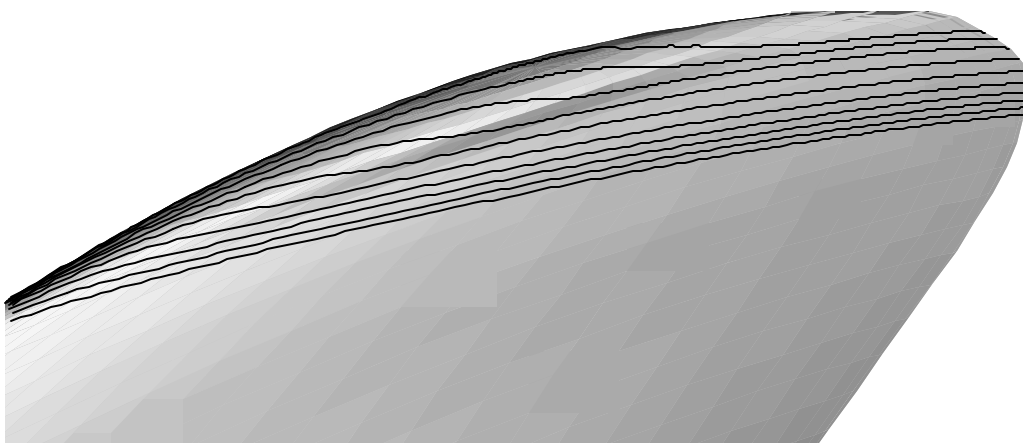|	
Unsteady thrust	1.3 % of mean thrust
Unsteady torque	0.7 % of mean torque
Unsteady vertical force	0.5 % of mean thrust
Unsteady side force	0.7 % of mean thrust

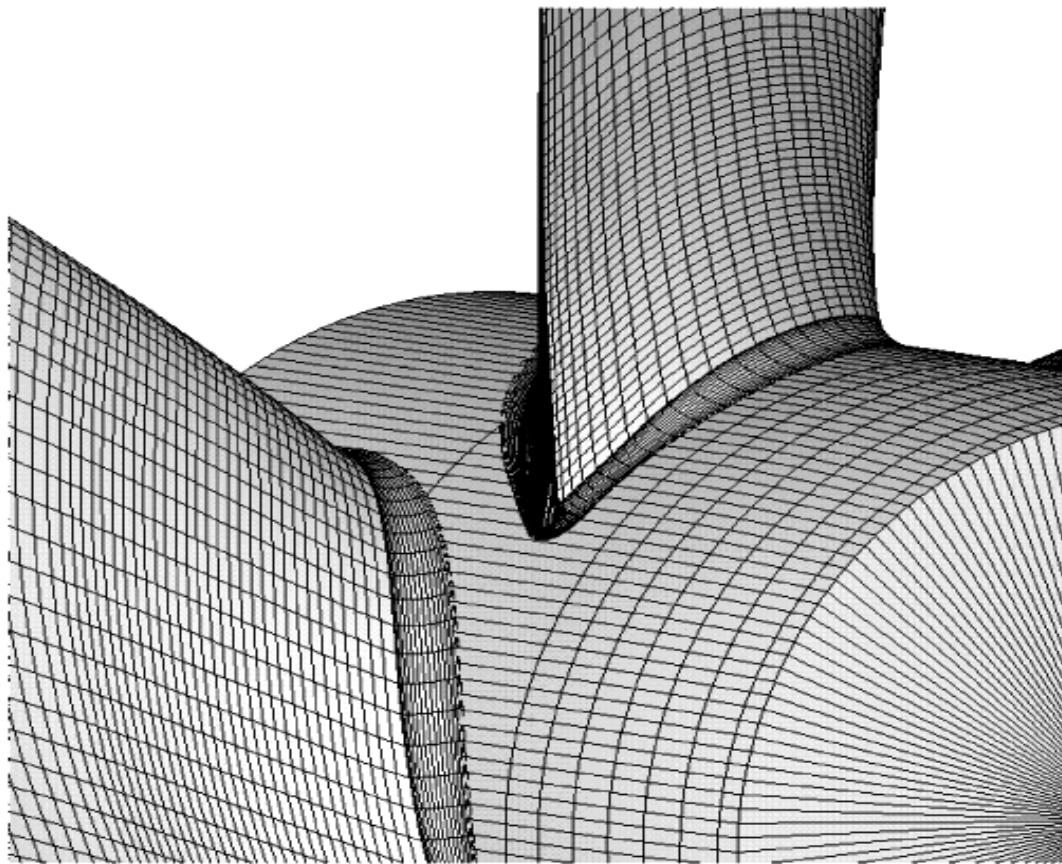Fig. 8a. Flow over FRV 40 propeller tip bulb

Fig. 8b. FRV 40 propeller blade surfacing and root fillets

Propeller Description:

Number of Blades: 5
Diameter: 14.1 feet (4.297 m)
Expanded Area Ratio: 0.637
Right Hand Rotation
Thickness Section: NACA 66 (DTMB Modified)
Camber Section: 3-D from a=0.8 meanline
Material: Nickel-Aluminum-Bronze (ABS Type 4)

r/R	C/D	T/C	P/D	f/C ×100	Skew (deg)	Rake/D ×100
0.25	0.190	0.354	0.404	-3.00	5.90	0.66
0.30	0.202	0.223	0.499	-1.57	-0.36	-0.06
0.40	0.227	0.144	0.713	1.05	-6.50	-1.54
0.50	0.253	0.102	0.929	2.62	-8.91	-2.46
0.60	0.280	0.072	1.026	3.20	-9.05	-2.48
0.70	0.306	0.059	0.966	2.19	-7.01	-1.78
0.80	0.327	0.052	0.828	0.68	-2.81	-0.64
0.90	0.321	0.054	0.687	0.08	4.17	0.80
0.95	0.269	0.065	0.627	0.02	9.13	1.58
1.00	0.000	0.000	0.570	0.00	15.41	2.36

Fig. 9. FRV 40 propeller geometric characteristics

A 324 mm. diameter model propeller was constructed and tested in open water. Open water test results are shown in Fig. 10.
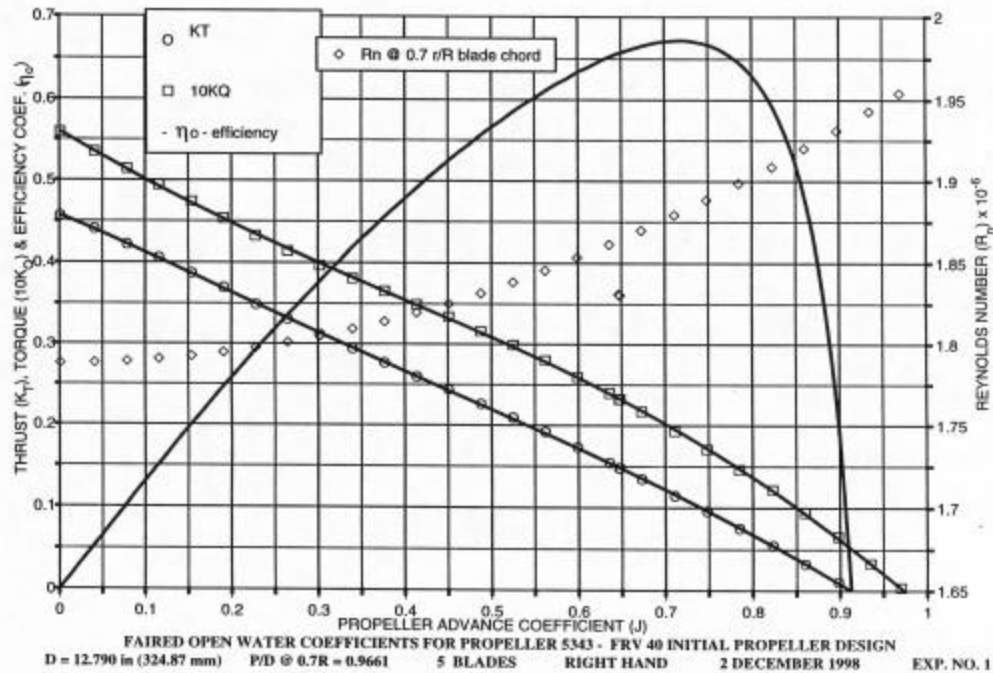

Fig. 10. Open water characteristics curves for design propeller model 5343

H. Final Design Powering

   The hull model was equipped with the following major items; redesigned bow, redesigned centerboard, actuated flap rudder, the base line skeg, and the final design propeller. The powering test results are shown in Fig. 11. With 2250 kW installed shaft power, the ship is predicted to achieve a trial speed of 14.4 knots in calm water at the 2520 mt displacement condition.

I. Cavitation Testing

The cavitation testing of the fully appended model was performed in the US Navy's William B. Morgan Large Cavitation Channel [7], located in Memphis, TN. Fig. 12a shows the FRV 40 model in the test position. Fig. 12b is a sketch of the facility. The model is held fixed, at the top of the test section and water flows by at close to full scale speeds. The channel is depressurized in order to achieve the proper cavitation number and simulate full scale cavitation conditions. The presence of the hull model provides the best simulation of full scale inflow characteristics to the propeller. Free surface wave making is suppressed. Static head due to the stern wave is accounted for in the setting of the chamber pressure. In this case, the propeller RPM was set by the torque identity method in which the propeller torque in the cavitation tunnel is matched to the torque from the model self propulsion test in the linear towing tank.

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        STILL AIR DRAG REF. AREA    2465.0 SQFT  ( 229.00 SQ METERS)
        WIND DRAG COEF.   0.75        POWER MARGIN FACTOR   1.00

    SHIP SPEED                EFFECTIVE        DELIVERED     PROPELLER
                              POWER- PE        POWER- PD     REV. PER
    (KTS) (M/S)              (HP)    (kW)     (HP)    (kW)     MINUTE
     2.0   1.03               4.1     3.1      6.6     4.9      17.6
     3.0   1.54              13.5    10.1     21.5    16.0      26.2
     4.0   2.06              31.3    23.4     49.4    36.8      34.8
     5.0   2.57              60.3    45.0     94.1    70.2      43.3
     6.0   3.09             103.0    76.8    159.1   118.6      51.7
     7.0   3.60             162.7   121.3    249.2   185.8      60.1
     8.0   4.12             244.9   182.6    371.3   276.9      68.5
     9.0   4.63             357.9   266.9    536.3   399.9      77.1
    10.0   5.14             510.8   380.9    758.0   565.2      85.9
    11.0   5.66             713.3   531.9   1050.8   783.6      95.1
    12.0   6.17             983.3   733.2   1440.8  1074.4     104.8
    13.0   6.69            1342.8  1001.4   1965.3  1465.5     115.1
    14.0   7.20            1805.7  1346.5   2646.6  1973.6     126.0
    15.0   7.72            2398.1  1788.3   3536.0  2636.8     137.4
    16.0   8.23            3203.1  2388.6   4768.9  3556.2     150.0

    SHIP          EFFICIENCIES (ETA)          THRUST DEDUCTION   ADVANCE
    SPEED                                     AND WAKE FACTORS    COEF.
    (KTS)  ETAD   ETAO   ETAH   ETAR   ETAB  1-THDF 1-WFTT 1-WFTQ  ADVC
     2.0   0.625  0.675  1.005  0.920  0.620  0.885  0.880  0.850  0.720
     3.0   0.630  0.675  1.005  0.925  0.625  0.885  0.880  0.850  0.725
     4.0   0.635  0.675  1.010  0.935  0.630  0.885  0.875  0.850  0.725
     5.0   0.640  0.675  1.010  0.940  0.635  0.885  0.875  0.850  0.725
     6.0   0.645  0.675  1.015  0.945  0.635  0.885  0.870  0.850  0.725
     7.0   0.655  0.675  1.020  0.950  0.640  0.885  0.865  0.850  0.725
     8.0   0.660  0.675  1.025  0.955  0.640  0.885  0.860  0.845  0.725
     9.0   0.665  0.675  1.035  0.955  0.645  0.885  0.855  0.840  0.720
    10.0   0.675  0.675  1.040  0.960  0.645  0.885  0.850  0.835  0.710
    11.0   0.680  0.675  1.045  0.965  0.650  0.885  0.845  0.830  0.705
    12.0   0.680  0.670  1.050  0.965  0.650  0.885  0.845  0.830  0.695
    13.0   0.685  0.670  1.050  0.970  0.650  0.885  0.840  0.825  0.680
    14.0   0.680  0.665  1.050  0.975  0.650  0.885  0.840  0.825  0.670
    15.0   0.680  0.660  1.050  0.975  0.645  0.880  0.840  0.825  0.660
    16.0   0.670  0.655  1.045  0.980  0.640  0.880  0.840  0.825  0.645
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   Fig. 11. Predicted powering characteristics of the NOAA FRV 40, as represented by model 5522-1 and design propeller model 5343, fully appended, with still air drag, no power margin

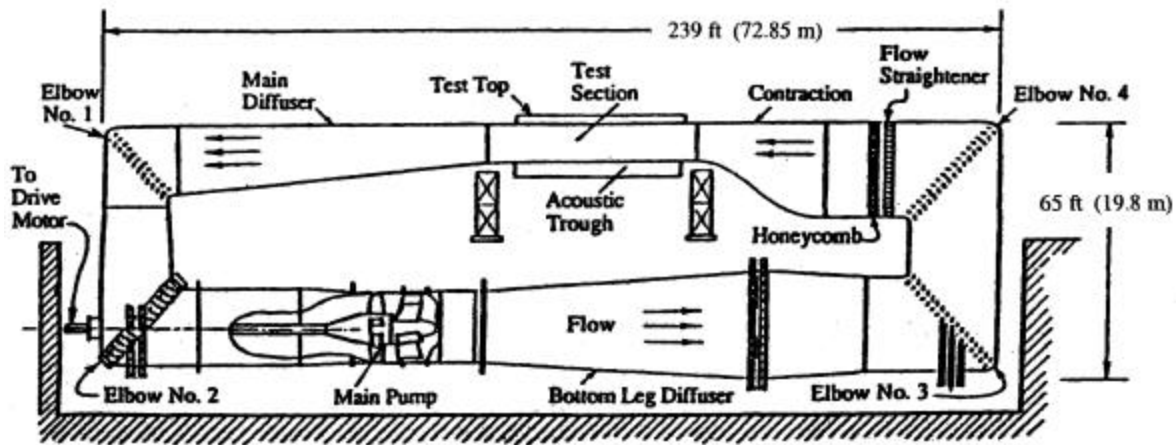Fig. 12a. FRV 40 model in large cavitation channel

Fig. 12b. Diagram of large cavitation test facility

The FRV 40 is the first research ship to be tested in this facility for cavitation. The test results indicate that the design propeller produces no cavitation of any kind at the 11 knot quiet operating condition. At the 4-knot tow load case there was a fully developed suction side tip vortex cavitation and thin patches of leading edge sheet cavitation on some of the blades. This cavitation was judged to be benign and should not cause any blade surface erosion. Fig. 13 shows the slight cavitation in the tow condition.

Scaling the experimental data to full scale provides a prediction that tip vortex cavitation inception will be at 12.7 knots. The application of an experimental uncertainty factor results in a worst-case prediction value for cavitation during free running operation at 11.2 knots full scale.
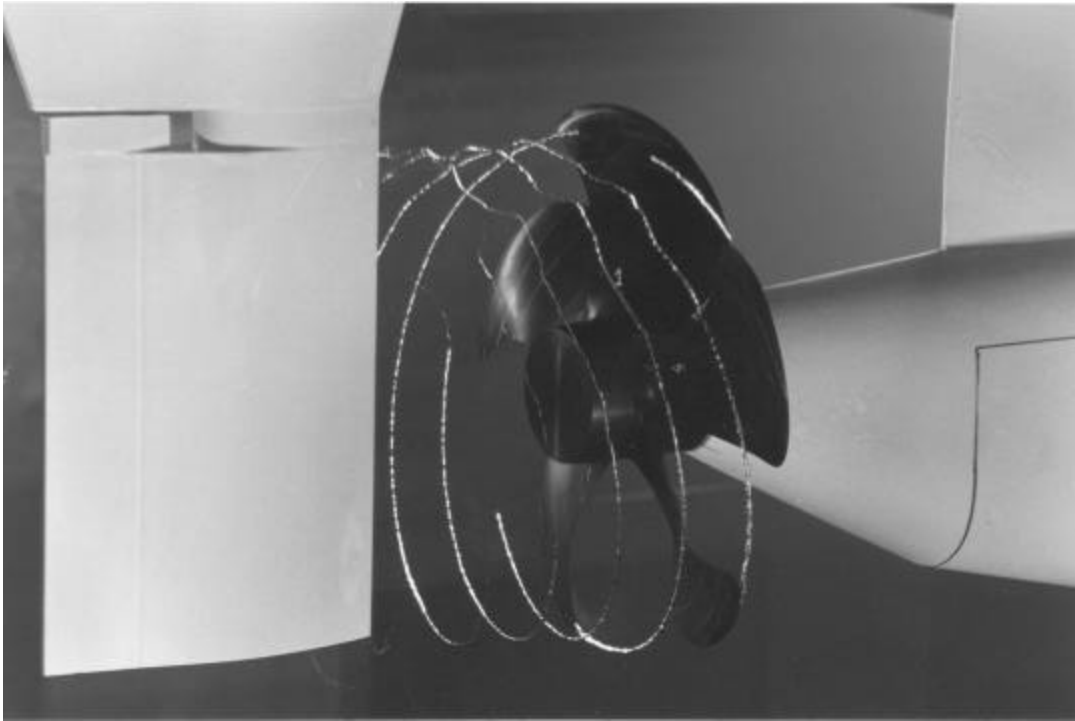
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Fig. 13. Slight cavitation in 4 knot tow condition at maximum engine torque

V. SUMMARY

Bubble sweepdown has been a persistent problem on oceanographic research vessels for several decades. The FRV 40 design makes use of previous bubble sweepdown experience and is the first ship hull form specifically designed to minimize the effects of bubble sweepdown on hull mounted sensors through shaping the forebody and adoption of the bulbous forebody feature. In addition, at the 11 knot quiet operation speed, this hull form has excellent powering and resistance characteristics. The FRV 40 uses a centerboard to deeply submerge some sensors and alleviate bubble sweepdown effects. Both the centerboard and rudder underwent design iteration in order to significantly reduce their drag.

The reduction of propeller hydrodynamic noise was recognized early in the FRV 40 program as critical to the mission success of the vessel. Special efforts were undertaken to provide a hull with a generous propeller clearance and a skeg with good wake characteristics for uniform inflow to the propeller. The skeg design was an adaptation of a skeg developed for the U.S. Navy Sealift Technology Development Program, and the uniformity of wake at the critical outer radii is as good as the wake associated with traditional open shaft and strut systems. Propeller design was undertaken according to U.S. Navy propeller design practices for the design of quiet propellers. In order to minimize tip vortex cavitation, a large diameter propeller, unloaded propeller tips, and a tip bulb are featured in the design. Tests at the U.S. Navy's Large Cavitation Channel show that the propeller will be able to operate cavitation free at the critical 11 knot quiet operation speed.

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